Open Science in Dinosaur Paleontology

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**Abstract**

Research is in the midst of a period of global terraform, usually heralded under the banner of 'Open Science'. Open Science is a response from communities to an increasingly digital ecosystem, enabling new practices to emerge. Three of the major pillars of Open Science include Open Access, Open Data, and Open Source. The global paleontological community is slowly adapting to each of these as part of its culture, raising new questions around scientific practices, data standards and interoperability, and the role of paleontological research in a modern society. This chapter discusses some of the progress that the paleontological community has made in shifting towards open practices, and considers some potential avenues for the future of the field.

**Introduction**

Dinosaur paleontology originated through the efforts of a handful of researchers, based in just a few areas of the world. Publication was an informal affair by today's standards, with little expectation of peer review, and in many cases no mention of where important specimens were deposited. The initial report of *Triceratops horridus* filled scarcely a page of text (Marsh 1889). The situation changed drastically, particularly during the mid-20th century, as the scientific community grew, more publication venues were launched, and increasingly rigorous standards of publication were put into place. Yet, practical limits on manuscript size as well as conservative research practices either intentionally or unintentionally kept the data behind manuscripts largely in the dark. Revolutionary morphometric studies during the 1970s (e.g., Dodson 1975) presented the final research output of increasingly massive datasets, but the measurements behind them were typically unavailable (due in part to limitations on space in physically printed copies). Research papers might then be often easily accessible to those with institutional library access, but individuals at small institutions or in far-flung areas might have to wait months to get a grainy facsimile of papers, or an original reprint courtesy of the authors.

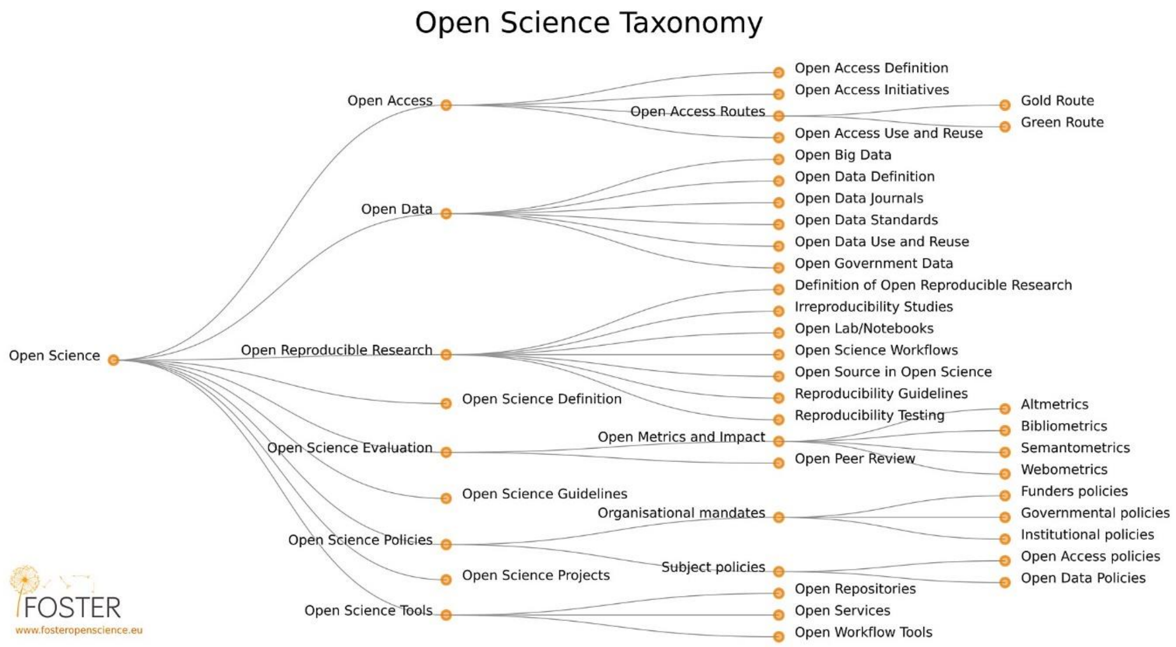
By the beginning of the 21st century, digital publication further transformed the process and presentation of dinosaur research. Ethical standards were formalized, often requiring explicit confirmation of specimen availability in a permanent repository, as well as the dissemination of supporting raw data such as cladistic matrices and measurements. Many publications, including those from the early days of paleontology, have now become easily (and often freely) available. In some cases, even the specimens themselves are available for download as 3D scans.

Although the fairly small field of dinosaur paleontology has often been a fairly collegial one, it too has had to grapple with issues of long-term reproducibility of research accessibility of publications,

as part of wider changes in the global research system. In this chapter, we address the role of "open science" in dinosaur paleontology.

**What is Open Science?**

The primary goal of scientific research is dissemination and re-use of knowledge for the betterment of humanity. Open Science (OS) can be defined as "…transparent and accessible knowledge that is shared and developed through collaborative networks", based on a recent systematic review (Vicente-Saez and Martinez-Fuentes 2018), and represents an attempt to re-align current scientific practices with its fundamental goal. It is also often used interchangeably with 'Open Scholarship' or 'Open Research'. It is unclear who actually coined the term 'Open Science', when it began to enter mainstream use, and what the philosophical basis for it is; something which makes it quite distinct from its sister movements such as Open Source. No universally accepted definition currently exists, and OS benefits from being conceived of as a 'boundary object', in which there is a common but flexible definition between communities of practice, but within those communities there is a generally understood definition (Moore 2017). Such complexity can be emphasised in current taxonomies (Pontika et al. 2015) that help to describe the different aspects of OS. This includes, but is not limited to, Open Access to research articles, Open Data, Open Reproducible Research, Open Science Evaluation, Open Science Policies, and Open Science Tools (Figure 1). Each of these are concepts designed to help improve the scientific process in some way, typically through injecting transparency at key points of the research life cycle. It is worth noting though that, in this widely used taxonomy, Open Science is a concept again based purely on outputs or processes, and seems divorced from any cultural or philosophical basis. In this way, it is perhaps equivalent to Open Source as a pragmatic offshoot of the value-based Free Software Movement, which was based on the four essential freedoms[1]. However, an equivalent basis for OS has yet to be formulated.




[1] (1) The freedom to run the program as you wish, for any purpose; (2) The freedom to study how the program works, and change it so it does your computing as you wish; (3) The freedom to redistribute copies so you can help others; (4) The freedom to distribute copies of your modified versions to others. (https://www.gnu.org/philosophy/free-sw.en.html)

Figure 1. A taxonomy of Open Science, according to FOSTER.

As such, OS currently can be best understood as a hierarchical combination of core practices. Often these are advocated for, and sometimes dogmatically on social media, based on foundational principles such as increased rigour, transparency, and accountability that should perhaps be inherent within the scientific endeavour. When discussing OS, often its proponents or supporters will appear to switch between discussing principles, practices, predicted outcomes, or processes, without appropriate consideration of how these things are linked. However, what this suggests is that the boundary between OS and 'normal', or traditional, science is not clear, and there are some who argue that OS should just be called science, as the principles and practices of OS are realistically those that should underpin strong research (Watson 2015). For example, transparency, reproducibility, and collaboration should be aspects that underpin virtually all research, not just that which is labelled as OS. I It is with acknowledgement of this varied understanding that we discuss OS further in the context of dinosaur research.

In spite of this fuzziness around the boundaries, understanding, and definition of OS, there have been major advances in global policies relating to OS in the last decade, at an institutional, organisational, and national level (Figure 2). Most of these have focussed on one particular area of OS, called Open Access (OA), which refers to the practice of making research articles available online at no cost to readers, and in a way that the content is fully re-usable without restriction (Tennant et al. 2016; Suber 2007).

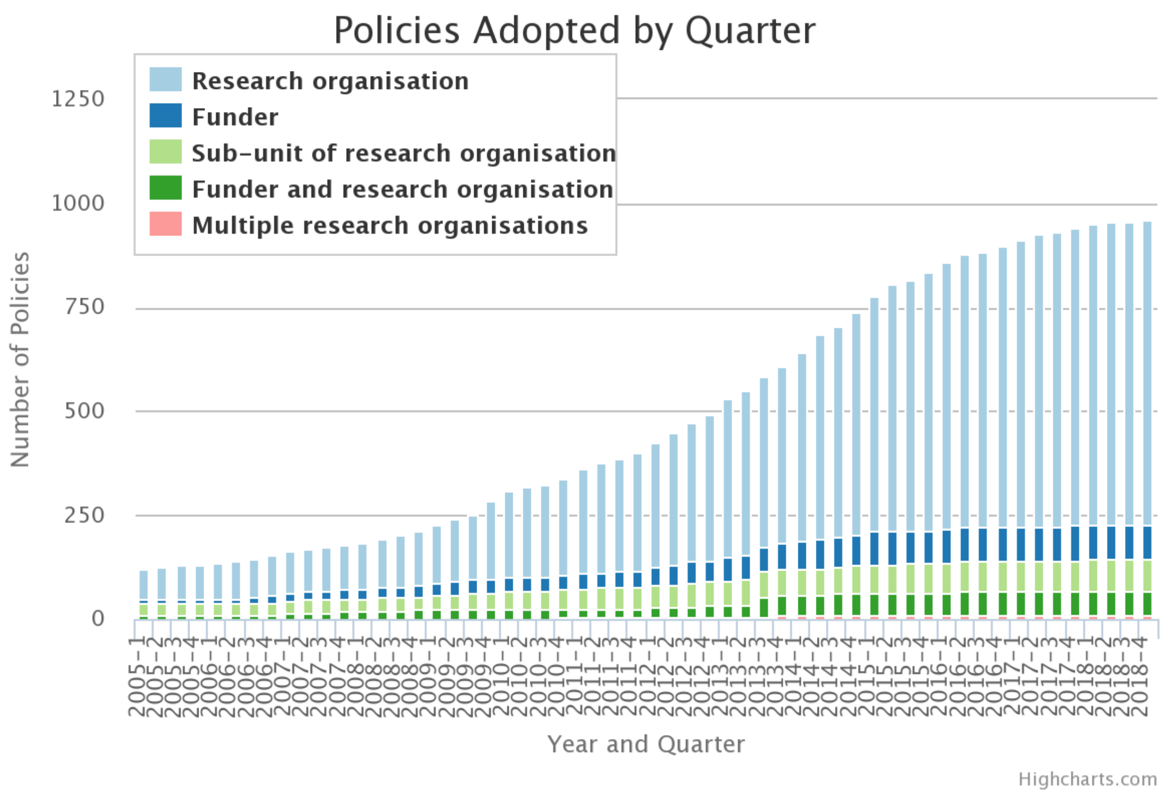



Figure 2. The Registry of Open Access Repository Mandates and Policies (ROARMAP) charts the growth of Open Access mandates and policies adopted by universities, research institutions and research funders. http://roarmap.eprints.org/

There has been little geographic unity behind the development of OA, and the present landscape of OA publishing is very fragmented, complicated, and heterogeneous. The National Institutes of Health (NIH) Public Access Policy in the USA (https://publicaccess.nih.gov/index.htm) and the Horizon 2020 Open Access policy in the EU (http://ec.europa.eu/research/participants/data/ref/h2020/grants_manual/hi/oa_pilot/h2020-hi-oa-pilot-guide_en.pdf) (now being accelerated through the development of 'Plan S') were major steps in driving OA forward in the global north in the last decade. OA has had a strong foundation in developing countries thanks to initiatives like the Scientific Electronic Library Online (SciELO), which launched in 1997, four years before the term 'Open Access' itself was conceived as part of the Budapest Open Access Initiative. In Africa, the recent launch of the Africa Open Science Platform shows that whatever Open Science is, it is becoming a global phenomenon (Participants of African Open Science Platform Strategy Workshop et al. 2018).

Despite this growth, it is estimated that around only 28% of the total published scholarly literature was publicly available in 2018, although the percentage has grown at a faster rate in recent years (H. Piwowar et al. 2018a). Within this system, there have now been countless innovations around OS, including discovery engines, data services, annotation tools, and new peer review and publishing platforms, as well as dozens of research articles that have investigated the various dimensions of OS (J. Wilkinson 2017; Shen 2017; Björk 2016; Laakso and Björk 2016; McKiernan et al. 2016; Chen and Olijhoek 2016; Morey et al. 2016; Tennant et al. 2017). Each of these have impacted the field of paleontology in varying ways.

**Open Science in Paleontology**

Traditionally, paleontology is stereotyped by those outside the field (and sadly, sometimes those within the profession) as an old-school research discipline, composed of dusty specimens resting dormant in museum basements, magnifying glasses, and an unhealthy association with all sorts of toothbrushes for digging up and cleaning fossils. However, over the past several decades, paleontology has undergone somewhat of a renaissance, as with many other research fields, as it has adapted to an increasingly digital, openly collaborative, and cross-disciplinary research ecosystem. Contemporary paleontology regularly includes aspects from across a range of different disciplines, including biology, ecology, evolution, engineering and mathematics, chemistry, and physics; it has even spurred "new" sub-fields including Paleoinformatics and Paleobiology as a consequence of this. As such, developments in OS in those fields are at least partially reflected in paleontology as part of a natural inter-disciplinary progression.

Discussion of the issue of reproducibility (beyond specimen availability) does not seem to have permeated broadly into paleontology, and indeed dinosaur paleontology often seems to more frequently follow rather than lead in this area. This should be a little concerning, given a trend towards more statistical research in paleontology, and also in related fields such as ecology and evolution. Elsewhere, questionable research practices (QRPs) have been widely documented (Fraser et al. 2018). These QRPs include factors such as p-hacking, cherry picking statistically significant results, and 'hypothesizing after the results are known' (HARKing). Other research fields are directly experiencing what is commonly known as a 'reproducibility crisis' as part of this (Fanelli 2018; Open Science Collaboration 2015; Munafò et al. 2017), driven by a combination of factors including perverse publication incentives, and which many aspects of OS aim to try and resolve.

*Society statements on Open Science*

At the moment, it does not appear that any single learned society in the field of paleontology has a statement on Open Access, or any other element of Open Science. Although many societies have in-house or outsourced publishing operations, thus receiving income generated from publishing services, often an explicit statement on openness from the society itself is not published beyond policies concerning specimen deposition in public museum collections.

This absence seems partially at odds with the proposed mission statements of many of the societies. If we look at the missions of The Palaeontological Association (PalAss): "The Palaeontological Association was founded in 1957 to promote the study of palaeontology and its allied sciences through publication of academic journals (*Palaeontology*, *Special Papers in Palaeontology*, and *Papers in Palaeontology*), the *Newsletter*, and *Field Guides*; holding regular meetings and field excursions; and funding a program of annual grants and awards."

And The Paleontological Society: "The Paleontological Society is an international non-profit organization devoted exclusively to the advancement of the science of paleontology: invertebrate and vertebrate paleontology, micropaleontology, and paleobotany."

Based on statements like this, it is clear that both have scientific advancement at the core of what they do. Thus, it seems a point of tension that that widespread, public access to research that they publish is often limited, even though the two are very much connected. At least part of this could be due to the potential revenue disruption that OA could bring; in which case, learned societies may need to reconcile the different elements of openness with their mission statement and other critical operations (e.g., administering grants, hosting conferences) that create tension in this space. It might also be the case in future that some societies need to reconsider their relationships with commercial publishers (e.g., PalAss and Wiley), who often generate enormous profits at the expense of the public purse, thus creating another financial tension between the mission statements of societies, sustainability of the societies, and the business models of some publishers.

**The growth of Open Access in paleontology**

It is now an increasingly common view among researchers and science policy makers that research that is funded by public funding agencies must be made OA, and that not making it so is an inappropriate practice (unless the authors are under specific constraints). This is one of the key moral arguments underpinning OA, relating to the fundamental freedoms of access and re-use. The documented benefits of OA to research articles are numerous and significant, mostly thanks to their digital format:

- Rapid publication and sharing;
- Relatively low cost due to the lack of printing;
- Fewer restrictions on length or colour figures;
- And ease of access to wider audiences.

Furthermore, research articles that are freely available to all readers are typically cited more frequently than those which remain behind paywalls, something known widely as the 'open access citation advantage'(H. Piwowar et al. 2018a; Tennant et al. 2016).

| Google Scholar rank (2017) | Publication | h5-index | h5-median | Publisher | Impact Factor (2017) | APC (USD) | Postprint embargo (months) | Preprints allowed |
|---|---|---|---|---|---|---|---|---|
| 1 | Palaeogeography, Palaeoclimatology, Palaeoecology | 39 | 46 | Elsevier | 2.375 | 2850 | 0-12 | Yes |
| 2 | Journal of Vertebrate Paleontology | 25 | 37 | Taylor and Francis | 2.19 | 2000 | 0-12 | Yes |
| 3 | Cretaceous Research | 24 | 32 | Elsevier | 1.928 | 3300 | 0-12 | Yes |
| 4 | Palaeontology | 23 | 35 | Wiley | 3.73 | 3250 | 12 | Yes |
| 5 | Review of Palaeobotany and Palynology | 23 | 32 | Elsevier | 1.665 | 3300 | 0-12 | Yes |
| 6 | Journal of Paleontology | 23 | 28 | Cambridge University Press | 1.353 | 2835 | 12 | Yes |
| 7 | Journal of Systematic Palaeontology | 22 | 32 | Taylor and Francis | 2.326 | 2950 | 0-12 | Yes |
| 8 | Paleobiology | 22 | 30 | Cambridge University Press | 2.4 | 2835 | 12 | Yes |
| 9 | Acta Palaeontologica Polonica | 20 | 24 | Polish Academy of Sciences | 1.887 | 0 | 0 | Yes |
| 10 | Marine Micropaleontology | 19 | 28 | Elsevier | 1.874 | 2500 | 0-12 | Yes |
| 11 | Palaios | 19 | 25 | Society for Sedimentary Geology | 1.702 | 2700 | 12 | No |
| 12 | Lethaia | 18 | 24 | Wiley | 2.218 | 3300 | 12 | Yes |
| 13 | Palaeontologia Electronica | 17 | 23 | Coquina Press | 1.41 | 0 | 0 | No |
| 14 | Comptes Rendus Palevol | 16 | 21 | Elsevier | 1.433 | 1100 | 0-12 | Yes |
| 15 | Facies | 16 | 20 | Springer Nature | 1.367 | 3000 | 12 | Yes |
| 16 | Historical Biology | 16 | 20 | Taylor and Francis | 1.249 | 2950 | 0-12 | Yes |
| 17 | Bulletin of Geosciences | 16 | 19 | Czech Geological Survey | 1.395 | 0 | NA | NA |
| 18 | Geobios | 16 | 18 | Elsevier | 1.205 | 3000 | 0-12 | Yes |
| 19 | Paleobiodiversity and Palaeoenvironments | 15 | 20 | Springer Nature | 1.229 | 3000 | 0-12 | Yes |
| 20 | Paläontologische Zeitschrift | 13 | 19 | Springer Nature | 1.275 | 3000 | 0-12 | Yes |
| | | | | **Average** | 1.811 | 2394 | | |

Table 1. A comparison of the OA policies for the top-20 ranked Paleontology journals according to Google Scholar.

However, in spite of this, the vast majority of paleontological research remains inaccessible to the public (Figure 3); at least through any legal means. Here, we simply looked at a subset of the published paleontological literature from a 2-year interval (2015-16), extracting data based on the top-20 ranked journals according to Google Scholar from Scopus (Table 1). This time interval was selected as it meant that every single article could, in theory, be OA – either due to being APC-free, or having passed the embargo deadline for a specific journal policy (maximum 12 months), and thus being freely available to self-archive by authors. To check their OA status, we ran the DOI list for each journal through the Unpaywall DOI checker (https://unpaywall.org/check-dois) which provides a simple binary distinction between whether an article is OA or not. The methods, data, and all code as part of this simple analysis are available online (https://github.com/Meta-Paleo/OpenPaleo).

What is clear is that, in theory, virtually every single paleontology paper more than one year on from publication at any point could be made open access, for free, and at no risk to the authors. This is known widely as 'green OA', or self-archiving, where an author posts a near-final copy of their peer reviewed, accepted manuscript online in a repository or website independent of the publisher. Self-archiving is distinct from 'gold OA', in which a final version is made freely available by the publisher, which sometimes encounters an article-processing charge (APC). And yet, even looking at the most recent publication years, this enormous potential for total OA is clearly not the reality (Table 2, Figure 3). On average, just 27% of all articles are openly available, with this number decreasing to 15.9% once the fully OA journals are removed. There is a large amount of variation between journals, with some, such as the society-led Palaeontology having more than half of its published content between 2015-16 Open Access. At the other end of the spectrum, the most poorly performing journals are those published by Taylor and Francis (Journal of Systematic Palaeontology, 6.2%; Historical Biology, 4.6%) and Elsevier (Cretaceous Research, 1.9%; Geobios, 4.2%; Palaeogeography, Palaeoclimatology, Palaeoecology, 6.3%).

Because each journal here has a potential to be 100% OA through 'green' self-archiving (i.e., author-facing cost is not a factor), there must be other explanations for this relatively low proportion. Possibilities here include apathy, lack of understanding of self-archiving policies, lack of career

incentives for archiving, lack of time relative to other professional duties, or some other form of resistance. The relatively high proportion of OA for the journal Palaeontology could be due to recent developments in the UK and Europe regarding OA policies and mandates. However, overall the reasons for this picture are eminently unclear at the present, but remain a worrying trend within the paleontology community. This is especially so given that there are community-led discipline-specific repositories, such as paleorXiv (https://paleorxiv.org/), that facilitate the sharing of articles (and data and code) in order to comply with journal policies and make routes to OA as simple, inexpensive, and risk-free as possible.

| Publication | Closed Access | Open Access | Total | Proportion OA (%) |
|---|---|---|---|---|
| Cretaceous Research | 419 | 8 | 427 | 1.9 |
| Geobios | 72 | 3 | 75 | 4.2 |
| Historical Biology | 173 | 8 | 181 | 4.6 |
| Journal of Systematic Palaeontology | 81 | 5 | 86 | 6.2 |
| Palaeogeography, Palaeoclimatology, Palaeoecology | 460 | 29 | 489 | 6.3 |
| Lethaia | 84 | 7 | 91 | 8.3 |
| Palaios | 106 | 9 | 115 | 8.5 |
| Journal of Vertebrate Paleontology | 215 | 28 | 243 | 13.0 |
| Journal of Paleontology | 138 | 22 | 160 | 15.9 |
| Marine Micropaleontology | 75 | 12 | 87 | 16.0 |
| Facies | 49 | 10 | 59 | 20.4 |
| Paläontologische Zeitschrift | 98 | 20 | 118 | 20.4 |
| Comptes Rendus Palevol | 115 | 25 | 140 | 21.7 |
| Paleobiology | 66 | 15 | 81 | 22.7 |
| Paleobiodiversity and Palaeoenvironments | 60 | 14 | 74 | 23.3 |
| Review of Palaeobotany and Palynology | 212 | 88 | 300 | 41.5 |
| Palaeontology | 77 | 42 | 119 | 54.5 |
| Acta Palaeontologica Polonica | 0 | 135 | 135 | 100 |
| Bulletin of Geosciences | 0 | 64 | 64 | 100 |
| Palaeontologia Electronica | 0 | 132 | 132 | 100 |
| | | | | |
| Total | 2500 | 676 | 3176 | 27.0 |
| Excluding full OA journals | 2170 | 345 | 2845 | 15.9 |

Table 2. The proportion of Open Access (including free to read) and Closed access articles in the top-20 Palaeontology journals.

It seems strange that, in a field such as paleontology where public engagement and social attention are often extremely high with respect to other research disciplines, such a low level of public access to the research itself remains. Indeed, paleontologists often still resort to commercial file sharing sites to illicitly share their own articles that they no longer have copyright to, which creates significant legal confusion in scholarly publishing. For example, popular commercial sharing platforms such as ResearchGate have been subject to significant legal attention in the last year or so, and have been forced to remove millions of illicitly shared articles from their platform in an ongoing international legal campaign against some publishers (Chawla 2017; Price 2018). Such examples highlight the strange tensions that exist between commercial publishers, researchers, third-party platforms, and a general understanding of the rights and restrictions accompanying the scholarly publishing process; something that is often lacking within research communities (Lovett et al. 2017). The majority of purely OA journals do not encounter this issue because they provide licenses that both protect authors and enable wide re-use rights (e.g., CC BY).

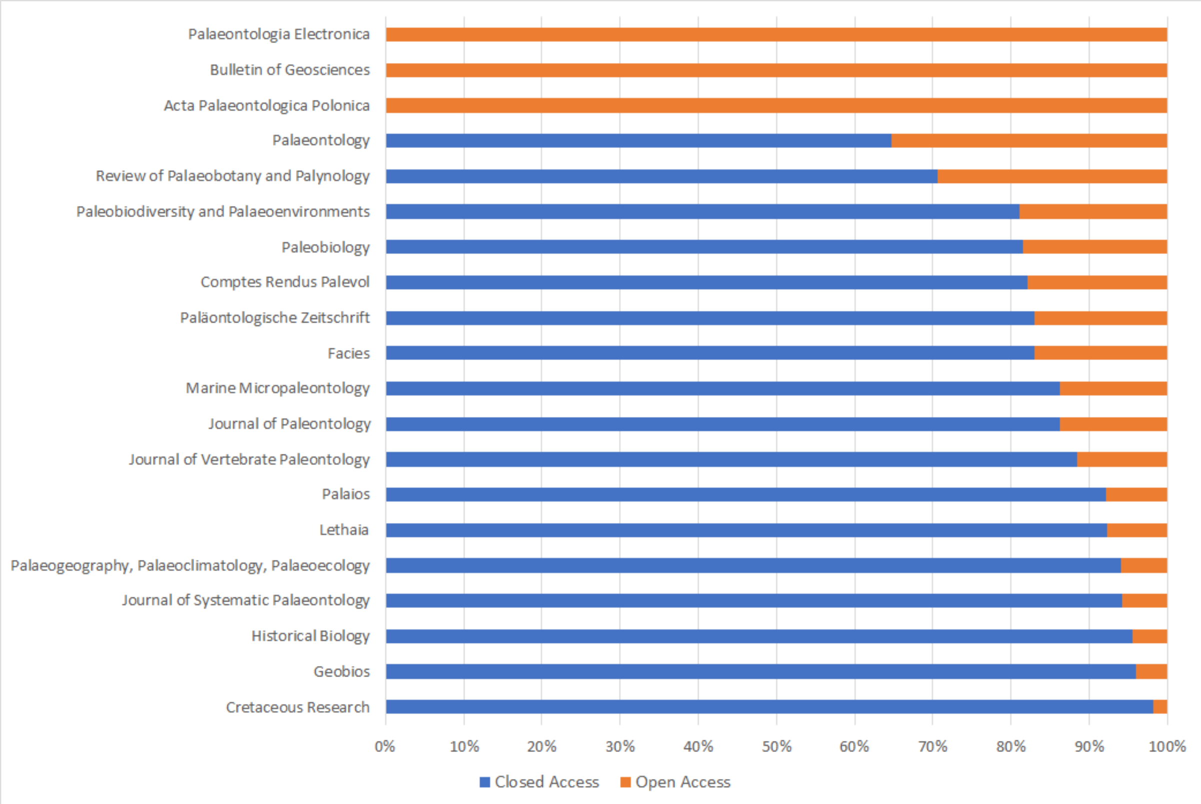



Figure 3. Proportions of OA publication (including green and/or gold options) for the top-20 ranked journals in Paleontology according to Google Scholar. See Table 2 for details.

As such, paleontologists who select 'closed access' journals perform a double-disservice, both to themselves by prohibiting access to and re-use of their work, and also to those who have funded them and the wider public. This remains despite the fact that virtually all paleontology journals allow free self-archiving to some degree, legally, and without risk to authors (see https://paleorxiv.github.io/journal_policies.html) (Table 1). Reasons for this vary, and range from simply not being aware of options available, journal policies being complex and off-putting, the perception that OA is lower quality than subscription-based publishing, a perceived lack of positive career incentives for OA, or simply being apathetic towards public access to research. Despite this complex system of resistance, the general uptake of OA across the globe is increasing (H. Piwowar et al. 2018a), and generally seen to be a 'good thing' in principle, from both a moral and scientific perspective. In terms of any potential citation advantage for OA in paleontology journals, the picture also appears to be mixed (Figure 4). Bearing in mind the relatively recent publication date for the sample here (2015-16), the citation distribution appears to be fairly low, with most articles receiving between 0-10 citations within this time, and few receiving more than 20 individual citations. There is no clear, universal OA citation advantage, although in several of the top-ranked journals (e.g., Journal of Vertebrate Palaeontology, Palaeontology) there does seem to be slight evidence for such a pattern. The citation distributions for each journal are almost invariably skewed towards the lower end of the spectrum, irrespective of journal rank or impact factor. Further analysis of these data will likely be able to shed more light on patterns of citation within the Paleontology literature.

Of note here also is that none of these journals appear to be experimenting with any form of 'open peer review' (Ross-Hellauer, 2017), lagging behind other interdisciplinary journals such as PeerJ and Proceedings B (published by the Royal Society), which frequently publish paleontological research.

Furthermore, some publishers such as Elsevier and Cambridge University Press still demand transfer of virtually all rights for a work, even when choosing an open license and paying for OA; this seems highly counter-intuitive, especially for those journals which are society-led.

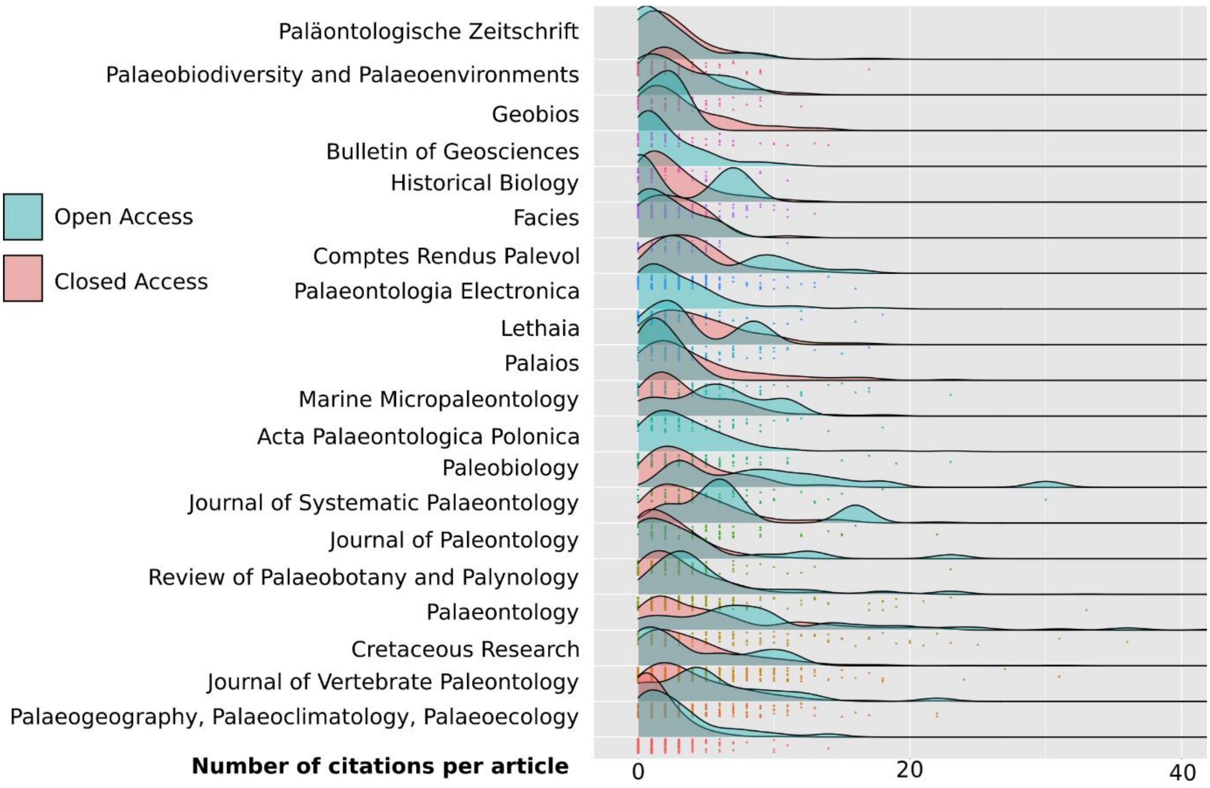



Figure 4. There is no clear, universal OA citation advantage for paleontology journals. Note that these data only cover a small, 2-year window.

Indeed, if we look at Google Scholar and the top-ranked journals in the field of paleontology (excluding any broadly interdisciplinary journals that paleontologists also publish in), only three (Acta Palaeontologica Polonica, Bulletin of Geoscience and Palaeontologia Electronica) are actually completely OA; all others are what is often termed ‘hybrid’ OA, whereby the journal itself remains subscription-based but selected articles can be paid for via author-facing charges to be made OA. Note that there are also complexities here regarding which licenses constitute ‘true OA’, with restrictively licensed or unlicensed content sometimes referred to as ‘bronze OA’ (Piwowar et al. 2018). Importantly, all three of these journals are owned by the research community themselves, and neither charge for OA, whereas all others are commercially owned and do charge (Figure 5). What we see, based on the top 20 journals in Paleontology according to Google Scholar, is an enormous rift between what commercial services, such as Wiley, Taylor and Francis, and Elsevier, offer, and what community-owned journals offer. Impact factors are broadly similar between both groups, and yet the commercial side challenges around $3000 USD for what the non-commercial entities offer; virtually exactly the same product. Thus, it makes little sense that paleontologists (many of whom are on a tight budget) would pay for something they could get for free; nonetheless,

this discrepancy and high cost of commercial journals might be one reason why OA has a relatively slow growth in the paleontology compared to other fields.

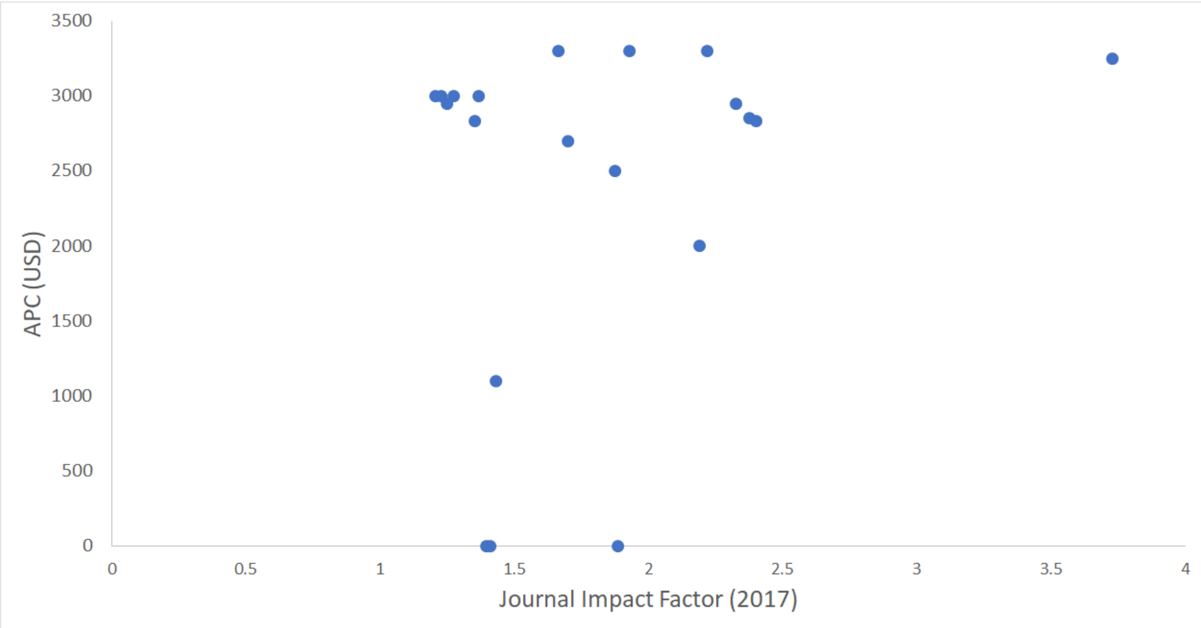



Figure 5. The journal impact factor for the top-20 journals plotted against their APC. This could be of use for palaeontologists in choosing whether or not to spend money on OA for equivalent ranked journals that are either lower price or much cheaper. (Pearson's product moment-moment correlation coefficient = 0.228, p = 0.321).

Another contributing factor to the seemingly low proportion of OA in Paleontology could be due to the increasing uptake of publication in non-specialist journals. The advent of 'megajournals' in the last decade – journals that typically are cross-disciplinary and assess articles based on their scientific merit rather than suitability or perceived impact – has been rather popular with elements of the paleontology community. A range of relatively new megajournals now publish paleontological research, including Scientific Reports and Nature Communications (by Springer Nature), Royal Society Open Science, PeerJ, and PLOS ONE. Comparative data on the amount of paleontological literature each of these publish is difficult to obtain. However, using the *rplos* package for R (https://github.com/ropensci/rplos), we can see that there has been an overall rise in the number of Paleontology articles published by PLOS since 2010 (Figure 6). This seems to have levelled off at around 10-15 articles per month, with a short decline in recent months since around the beginning of 2017. This might be due to increasing competition with the aforementioned journals, all of which are primarily funded through APCs. The current (January 2019) APC for Nature Communications is $5,200 USD before tax.

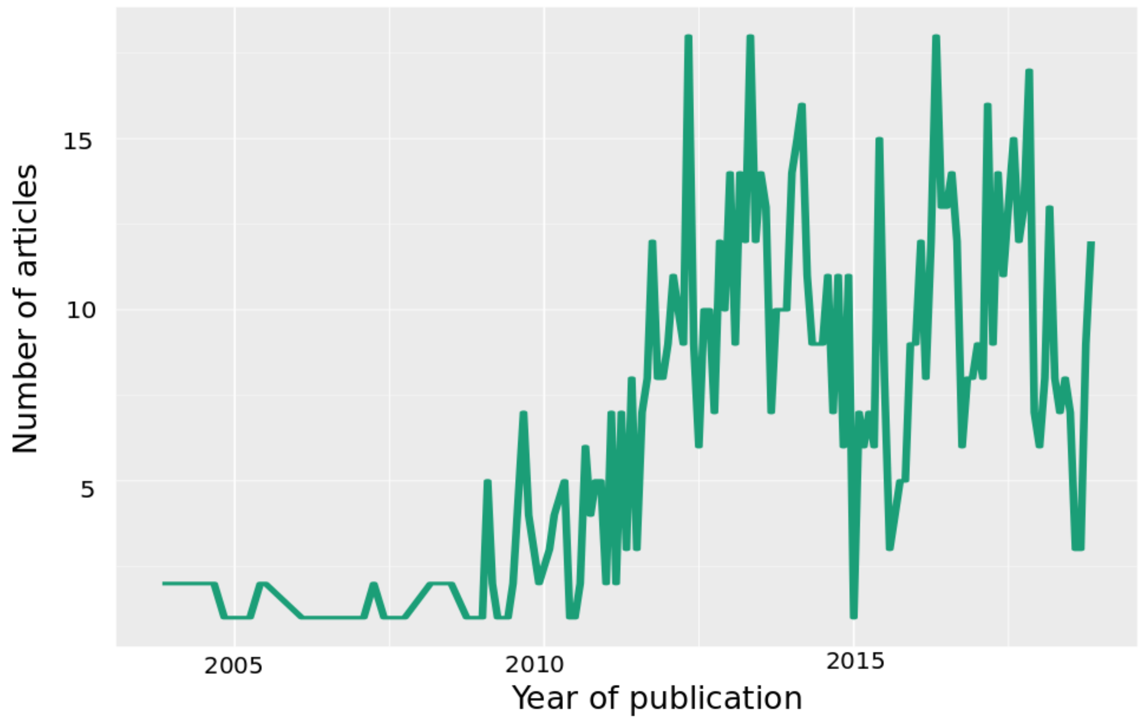



Figure 6. Publications of paleontology papers in PLOS. Note the decline around 2017, which could be due to the growth of competing journals such as PeerJ and Scientific Reports.

One key player for OA in paleontology is the journal Palaeontologia Electronica (PE). PE was one of the first freely downloadable and readable journals in paleontology, and launched its first issue two decades ago in 1998 (Macleod and Patterson 1998). The rationale behind PE was to use the power of emergent Web-based technologies to streamline the research communication process, and it has since become widely accepted by the paleontology community (Louys 2015). Almost uniquely among paleontology journals, PE maintains a free publication process for both authors and readers, thanks to sponsorship from The Palaeontological Association, The Society of Vertebrate Paleontology, The Paleontological Society, and the Western Interior Paleontological Society. However, more than 4 decades before the launch of PE, Acta Palaeontologica Polonica (APP) was publishing freely accessible content at no cost to authors, thanks to support from the Instytut Paleobiologii in Poland (https://www.app.pan.pl/history.html). APP became digital in 1991, and in 2005 joined the Directory of Open Access Journals (DOAJ). In 2009, APP finished digitising its back content, and provided free access to its complete archive of published research articles. Numerous other journals have followed suit, although the licensing protocols vary.

One deterrent for the early adoption of digital publishing (including open access) in dinosaur paleontology were concerns about the validity of names in the eyes of the International Commission on Zoological Nomenclature (ICZN). Initial recommendations required that even a digital-only publication must have a physical counterpart, partly out of fears that unethical researchers might churn out dubious names on websites with limited peer review, and that digital-only publications might be too ephemeral for long-term access. As a result, the first digitally-named dinosaur, *Karongasaurus gittelmani* (Gomani 2005), was accompanied by a printed and CD-ROM version. In 2012, the ICZN amended its rules to formally permit digital-only publications, greatly easing the

situation for digital-only journals (Polly 2013; International Commission on Zoological Nomenclature 2012). This was enabled in part by the rise of digital repositories to allow effectively permanent archival of digital journals.

## Open Data and Paleontology

In the last decade, there has been quite a strong movement towards open data from the paleontological community. This has been driven by a combination of several things, including increasing data-sharing policies and mandates from journals and research funders, increasing technological availability, and reduced costs for data sharing, and community-driven advocacy (Uhen et al. 2013). For an excellent overview of the pre-2000 history of databases in Paleontology, we recommended interested readers to see Benton (1999). In 2000, the term 'paleoinformatics' was coined as a counterpart to the growing field of 'bioinformatics', and related to the increasing value of data-driven paleontological research, and issues related to its digital creation, archiving, and retrieval (MacLeod and Guralnick 2000). Now, numerous organisations and journals across paleontology-related disciplines (e.g., ecology and evolution) have signed the Joint Data Archiving Policy, which requires that data supporting any publications be made publicly available (https://datadryad.org//pages/jdap).

In addition to making the text of the final publication available, availability of supporting data is another important practice of open science. At its most basic level, reproducibility requires that the specimen(s) upon which a study is founded must be deposited in a publicly accessible, long term museum collection. However, this in itself is still insufficient for true open science. In the case of studies using quantitative analysis (such as phylogenetic reconstructions or morphometrics), the raw data should also be accessible. As discussed below, this is also increasingly extended to two- and three-dimensional imaging data. Numerous data portals now exist that are utilised by paleontologists, and apply to a wide range of data types, including phylogenetic, morphological, GIS, and morphometric data (see Uhen et al. (2013) for a comprehensive overview of paleontological databases). Some of the most widely used examples are:

- Dryad (https://datadryad.org/)
- Figshare (https://figshare.com/)
- Morphobank (http://morphobank.org/)
- Morphbank (www.morphbank.net/)
- TreeBase (http://treebase.org/)
- MorphoSource (http://www.morphosource.org)

Davies et al. (2017) provided the following definition for data repositories: "Digital repositories should have the same qualities as repositories of physical specimens, in that they should ensure the long-term persistence and preservation of datasets in their published form, provide expert curation and stable identifiers for submitted datasets, and facilitate public access to data without unnecessary restrictions." Key aspects here are the sustainability of data, and the re-use facilitated by persistent identifiers (PIDs). If one were to extend this definition to fully conform to the FAIR principles (citation), it would have to include additional explicit components on findability and interoperability. As such, we propose extending this definition of a data repository to: "Digital repositories should have the same qualities as repositories of physical specimens, in that they should:

- Be registered and indexed within a searchable resource;

- Ensure the long-term persistence and preservation of datasets in their published form, and that even metadata are accessible should the data no longer become available;
- Provide expert curation and stable identifiers and additional enriched metadata for submitted datasets;
- Ensure that data are retrievable based on such identifiers and metadata;
- Make sure that the data creation protocol is universally implementable and with an appropriate authentication procedure;
- Ensure that data have a formal, accessible, shared language and format for knowledge representation;
- Be clearly licensed in a way that encourages and facilitates re-use based on community standards;
- And make public access to data easily accessible without unnecessary restrictions."

As well as data availability, code sharing is also a critical aspect of increasing the reliability, and reproducibility of the published record. Without data and code (including documentation for the coding environment, metadata, and dependencies) being available it actually becomes impossible to verify published research, including as part of the peer review process, and therefore is of critical importance to be shared alongside published manuscripts. A number of code sharing portals now exist, including GitHub and GitLab for example. However, uptake of these services appears to be fairly low, as many journals simply attach code and scripts, as well as data, in supplementary files to a manuscript, or linked to a data portal such as Dryad. Such methods of sharing do not take advantage of the power of platforms such as GitHub for project management, open collaboration, archiving (when linked with other platforms such as Zenodo), and version control. However, organisations such as ROpenSci – driven largely by ecologists – do commonly use GitHub, and provide a substantial amount of code through this service, and other portals, and have become widely adopted by paleontologists due to the strong overlap between disciplines. Platforms such as paleorXiv, based on the Open Science Framework, are integrated with services such as Figshare and GitHub to enable efficient collaboration and sharing of research outputs.

*Digitisation of fossils and computer-aided visualisation*

There has been great interest in applying virtual technologies to paleontological research, even termed a "digital revolution in paleontology" (Cunningham et al. 2014), which is helping to breathe new life into fossil-based analyses. By using virtual computational environments to create digital reconstructions, it is possible to access fossils in greater detail, and use this as the basis for investigating form and function in extinct animals (Lautenschlager 2016; Rahman and Smith 2014). Although the first computed tomography scans of fossils were taken in the late 1970s, it wasn't until the late 1990s and early 2000s that they became a relatively common tool within dinosaur paleontology. Due to the increasing power of computers and their relatively decreasing prices, digital technologies are becoming increasingly widespread, and have catalysed a wave of innovation in paleontology. This has been focused on several aspects:

1. Non-destructive sampling and extraction of fossil material.
2. Enhanced visualisations of fossil data, including of internal anatomy.
3. Digital restoration and reconstructions of damaged or distorted specimens.
4. Sharing of digital datasets, especially those of rare or difficult to access specimens.
5. Quantitative functional analyses of extinct animals.

One of most popular methods in this respect has been computed tomography (CT) scanning, which uses X-rays to generate a digital model of a specimen for further inspection. As a non-destructive technique, it is particularly useful for studying rare or valuable specimens and making data more widely available for future research. For a full list of techniques and available software now being used in paleontology, and some of their characteristics, see Cunningham et al. (2014).

Another key advantage for researchers here is that sharing of high quality research data is often associated with an increased citation rate for articles (H. A. Piwowar and Vision 2013; H. A. Piwowar, Day, and Fridsma 2007). As such, this can be appealing to researchers on an individual level due to the widespread treatment of citations as a form of 'academic capital'. A further driver for increased data sharing comes from the policy level, such as when national funders like the National Science Foundation in the US created a data sharing mandate, this catalysed the Journal of Vertebrate Paleontology to require data sharing for all articles it published from 2011 onwards (Berta and Barrett 2011).

*Licenses, standards and best practices*

Best practices for sharing of phylogenetic data, which is popular in paleontology, already exist in an easily digestible format, and help to improve the state of archiving, sharing, and re-use (Cranston et al. 2014). Here, CC0 is recommended for datasets – equivalent of waiving rights – in order to improve data interoperability, as well as universal recognition and simplicity for re-use. CC BY (Creative Commons Attribution license), however, also meets these criteria, while making attribution (citation) an explicit legal right for creators. Cranston et al. (2014) also recommend full methodological transparency, including sharing of all scripts that were used to generate results so that analyses can be fully replicated. This includes being explicit about analysis and result matching, and the exact procedures that were employed, which can be simply added as part of an accompanying README file to the analysis scripts themselves.

In 2017, a group of researchers on digital morphology published a series of baseline recommendations, standards, and best practices for the publication of 3D morphological data, particularly within the context of fossil organisms (Davies et al. 2017). The driver behind this was that the lack of published data behind research articles meant that they could not be verified or replicated, easily built upon, and that such unpublished data are ultimately destined to be lost to science. One of the greatest parts of this article was that consensus appears to have been achieved at a community level for increasing the utility of digital morphological data, which is a valuable step forward in creating a more sustainable research framework for paleontology. The article also continuously highlighted the importance of appropriate metadata, which is important for helping data to meet the FAIR principles of open data (Mons 2018; M. D. Wilkinson et al. 2016).

There are discipline-specific considerations that must be mentioned here. For example, it is not always clear who has ownership over digital data, particularly that obtained from museum collections dispersed around the world. Often, it is the case where researchers must sign permission forms that entitle a museum to retain all intellectual property and ownership rights for many data gathered by either internal or visiting researchers, which would prohibit then sharing that data to a third party, including data sharing platforms and publishers. Such permission forms do little to promote the advancement of paleontological research, and conflict with recommendations and a general movement towards more liberal licenses, such as CC BY (Hagedorn et al. 2011). Indeed, such policies seemingly run counter to a general professional ethic of fossils as global heritage. However,

it does raise a clear question of data ownership, between the research funders, the researcher institutes, the researchers themselves, the data collection facilities, and the publishers and data repositories. It is likely that this will not be resolved overnight and relates to wider issues of control and governance over public research. However, if the common goal of all stakeholders is to advance research, irrespective of ownership, then clearly adopting open licensing strategies with appropriate attribution of provenance is key.

Further considerations must be given about the risks for disclosing potentially sensitive information, such as where rare or valuable fossils were discovered, which could be exploited by the illicit fossil trade. Here, relevant laws must be taken into account; for instance, the Paleontological Resource Preservation Act (PRPA) prohibits unauthorized disclosure of detailed locality data for significant vertebrate fossil sites on federal lands in the United States. Another potential issue is the extraction and re-use of information often obtained from commercially copyrighted research articles (Dolven and Skjerpen 2011). However, facts and data often are not subject to the same copyright laws as other types of created content (Uhen et al. 2013), and it is unlikely that this will ever be a legitimate threat to the future of paleontological databases. However, it would be wise for the global paleontological community to pay attention to ongoing changes in copyright law that might impact the functionality and usage of research databases in the future.

At present, no-one has conducted a formal survey in to the state of open data requirements for paleontology journals, and the potential tensions this creates with other institutes. In the future, we anticipate that publishers, data service providers, and museums, will have to adopt new communal standards that aim to address the issues with sustainable access to digital paleontological data, including governance, technological development and maintenance, and cost. Reconciling this will be critical as digital techniques become increasingly adopted by paleontologists, data become more widely available, technologies improve, and with this an inevitable scaling up of research questions involving these; for example, multi-taxon comparative biomechanical studies.

**Examples of Open Science initiatives in paleontology**

*The Paleobiology Database and Fossilworks*

One of the largest compendia of fossil and associated data, the Paleobiology Database (PBDB) (http://paleobiodb.org/), was founded in 1998 by Charles Marshall and John Alroy. At the time of the writing this chapter, it includes more than 1.3 million individual fossil occurrences, more than 370,000 taxa and 670,000 opinions about them, drawn from more than 65,000 literature references, entered by 410 researchers from around the world. In 2013, the PBDB became fully openly licensed (CC BY 4.0) (https://creativecommons.org/2013/12/19/paleobiology-database-now-cc-by/), representing the over-ruling of a preceding confusing assortment of individually-assigned licenses from data enterers. The PBDB is now moving from strength to strength, having built a custom Application Programming Interface (API) (http://paleobiodb.org/data1.1/), the core PBDB Navigator (http://paleobiodb.org/navigator/) being open source, having a mobile application (https://itunes.apple.com/us/app/mancos/id541570878), and being the source of more than 300 official research publications (https://paleobiodb.org/#/publications). However, one potential issue with the PBDB is that it only presents a ‘snapshot’ of the fossil record, as the vast majority of data are based on specimens which have been formally published, and therefore excludes information about the vast numbers of unpublished specimens residing in museum collections (Marshall et al.

2018). Thus, there remains great potential for leveraging museum collections through digitisation to become more widely used for research purposes.

*Digital Dinosaur Fossils*

Easy digital accessibility of 3D data for dinosaurs is still more the exception than the rule, yet it is becoming more common. Early efforts to make dinosaur fossils digitally available were hampered to some extent by slow and expensive technology, lack of suitable long-term repositories, and fears over the effects of release of data “into the wild,” such as loss of revenue from replicas. Many early releases of 3D scan data were on an ad hoc basis, using CD-ROMs (e.g., Brochu 2003) or using repositories that weren’t necessarily meant just for these kinds of data. The most completely available dinosaur skeleton to date, a baby *Parasaurolophus*, was released in this fashion (Farke et al., 2013). Now, 3D data repositories such as MorphoSource provide more direct and easily searchable opportunities for distribution of digital dinosaur data. For instance, the holotypes for *Arkansaurus fridayi* (Hunt and Quinn 2018) and *Dynamoterror dynastes* (McDonald, Wolfe, and Dooley 2018) are available via this site. In other cases, researchers post scan data as supplemental information for their papers, as for the holotype of *Aquilops americanus* (Farke et al. 2014) and a disarticulated skull of *Tenontosaurus tilletti* (Thomas 2015). This contrasts with researchers or institutions who choose to post only non-downloadable previews of the data. Although these have educational value, utility for research and in-depth outreach (such as 3D printing) is limited.

*Outreach and paleontology*

Countless initiatives and projects launched by palaeontologists cover some form of public outreach and engagement. These range from social media, fossil festivals, through to citizen science initiatives and social learning spaces to bring amateur and professional paleontologists together. Such ‘social paleontology’ initiatives are open and inclusive spaces that support collaborative dialogues and scientific inquiry, while facilitating reciprocal engagement between researchers and non-specialists (Crippen et al. 2015). Many dinosaur paleontologists have an incredible track record of such activities, which is perhaps due to the relatively unique public interest, and impact on public culture, that paleontology enjoys compared to other research fields.

There is clearly a link here between outreach efforts and the wider advent of OS. For example, as mentioned above, the increasing availability of virtual fossils provides a powerful new way of engaging audiences interactively with fossil organisms, as well as developing a greater public understanding of evolution (Rahman, Adcock, and Garwood 2012; Garwood 2012; Lautenschlager and Rücklin 2014; Hendricks, Stigall, and Lieberman 2015). This demonstrates an additional value of open data in paleontology in providing the basis for open educational resources and for diverse forms of science communication, and especially in regions where paleontology is not formally taught as an education program (Pimiento 2015). In addition, there are now a number of high-profile podcasts (e.g., Palaeocast; http://www.palaeocast.com/) and blogs and blog networks (e.g., PLOS Paleo; https://blogs.plos.org/paleocomm/) that help to more widely disseminate paleontological research both within the community and to the wider public.

**Future considerations**

Understanding the impact of the various aspects of OS on the careers of individuals, as well as the wider research community and process, is important for the future of paleontology. This is especially so in terms of the perceived risks and barriers associated with increased openness. For example,

resistance to sharing data often comes from a desire for those who collected the data to hold on to it until they have performed all possible analyses on it and maximised its research value. Although poorly documented, another widely perceived risk is that of ‘scooping’, whereby other researchers could re-use the published data of others before they have had a chance to; this in theory places junior researchers at more risk, as they might take more time to perform experiments, and have relatively less history to build their reputations on (Callaway 2011). However, one could argue that researchers should not be rushing to publish research papers without fully exploring the data first; an issue which is generally part of a ‘publish or perish’ mentality in academic culture. These tensions are by no means unique to paleontologists, and part of wider systemic changes happening now around open science. However, the paleontology community is unique, and therefore will require special and careful consideration of the impact of open science on researcher careers, research processes, and the ethical and societal implications of these as paleontological research continues to move forward.

Irrespective of such issues, it should be noted that research articles that do not have the data used for them made public cannot be verified, critiqued, built upon as easily, or even reproduced, making it a much weaker scientific output than if the underlying data (and software) were shared. Indeed, this is one of the key drivers of the OS, and other palaeontologists have already suggested that immediate data sharing (raw and treated) at the time of publication should be mandatory (Cunningham et al. 2014). Such a view is also shared by the Peer Reviewer’s Openness Initiative, which individuals can sign to support transparency and rigour during the peer review process through aspects such as data and materials sharing (Morey et al. 2016). Therefore, there is still a strong tension between proper research conduct and doing what is best for science, and the social risks associated with wider sharing.

There would be substantial scope in combining the efforts of existing data repositories to connect together different forms of data. For example, the PBDB could be enhanced by adding phylogenetic data sets and matrices, source articles, taxon images and digital reconstructions, and other relevant morphological metadata captured by alternative repositories. This would help to provide a more intuitive, interoperable, and integrated structure from which to base future research on, as well as reduce redundancy in research and potential loss of information or data quality.

Paleontology began as a science focused on discovering, identifying, and description of fossil species. In the 19$^{th}$ and 20$^{th}$ centuries, the field became more about reconstructing the evolutionary history of life on Earth, and took on a more empirical, quantitative, deep-time approach to biological and geological research questions. Now, there are already sub-fields such as paleoinformatics and paleobiology that adopt a range of novel and cross-disciplinary approaches to old questions about extinct life (Reisz and Sues 2015; Jablonski and Shubin 2015). What will the future of paleontology be in an open science world? What new questions and research avenues will be unlocked as new techniques, practices, and cultural changes are adopted? We don’t have the answers to that right now, but we can be confident that the global paleontology community will continue to thrive, adapt, and evolve, just like the organisms we study.

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**Conflicts of Interest**

JPT is the founder of non-profit publishing platform paleorXiv; both authors are PLOS Paleo Community Editors. AAF is a volunteer editor for *PeerJ*.

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